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ANALYSIS OF THE MAGNETIC FIELD DISTRIBUTION IN THE PARALLEL PLATE RHEOMETER MEASURING SYSTEM

ANALIZA ROZKŁADU POLA MAGNETYCZNEGO W GEOMETRII POMIAROWEJ REOMETRU TYPU RÓWNOLEGŁYCH PŁYTEK

Key words: magnetic fluids, parallel plate geometry, rheological research, magnetic field distribution.

Abstract Magnetic fluids are materials whose physical properties can be changed by a magnetic field of a given intensity value. One of the fundamental research areas for determining the properties of magnetic fluids is rheological measurement. The basic method for determining the rheological properties of this type of smart material is by using rotational rheometers equipped with parallel plate measuring geometry. The paper presents the results of numerical simulation and experimental research on the magnetic induction distribution in the working gap for this type of measuring geometry. The conducted analyses allowed the influence of selected parameters on the uniformity of the magnetic field distribution in the magnetic fluid to be determined. The work paid attention to the problems occurring in the development of measuring systems for determining the properties of magnetic fluids under the conditions of a magnetic field.

Słowa kluczowe: ciecze magnetyczne, geometria równoległych płytek, badania reologiczne, rozkład pola magnetycznego.

Streszczenie Ciecze magnetyczne są to materiały, których właściwości fizyczne mogą być kształtowane za pomocą oddziaływania na nie polem magnetycznym. Podstawową metodą badawczą stosowaną do wyznaczania parametrów reologicznych cieczy magnetycznych jest pomiar na reometrach rotacyjnych z wykorzystaniem geometrii pomiarowej dwóch równoległych płytek. W pracy przedstawiono wyniki badań symulacyjnych oraz doświadczalnych rozkładu indukcji magnetycznej, w szczelinie roboczej dla tego typu geometrii. Przeprowadzone analizy pozwoliły na określenie wpływu wybranych parametrów na równomierność rozkładu pola magnetycznego w cieczy magnetycznej. W pracy zwrócono uwagę na problemy występujące przy opracowywaniu układów pomiarowych do wyznaczania właściwości cieczy magnetycznych w warunkach oddziaływania pola magnetycznego.

INTRODUCTION

Magnetic fluids (MF) are suspensions of particles with ferromagnetic properties in a carrier liquid (usually water or oil). Depending on the size of the particles, two types of magnetic fluid can be distinguished: ferrofluids (FF) composed of particles with a size of 5–15 nanometres [**L. 1**], and magnetorheological fluids (MRF) in which particles are of the order of 1–10 micrometres [**L. 2**]. In the case of magnetic fluids, there is the possibility of a reversible and rapid change in their rheological parameters, and even a change in the flow direction as a result of the influence of the magnetic field. They belong to the group of materials in which the fluid rheological properties change as a result of a stress state change in the internal structure [**L. 3, 4**]. There are a number of implemented, as well as potential, applications of magnetic fluids, such as seals, clutches, brakes, mechanical vibration dissipation systems, and bearing systems [**L. 5–8**].

Magnetic fluid rheological properties depend on a number of factors related to both the composition of the fluid and working conditions. The most important are the following: size, the shape of particles, their volume share in the carrier liquid, the physical (in particular magnetic) properties of particles, the rheological properties of the carrier liquid, as well as magnetic field distribution, the

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velocity and direction of magnetic fluid deformation, and the thickness of the working layer.

One of the fundamental research areas for determining the properties of magnetic fluids is rheological studies. The basic method used to determine the rheological parameters of MF is measurement on a rotational rheometer. There are known publications on the determination of MF rheological properties by using typical measurement geometry, i.e. cone-plate and coaxial cylinder geometry; however, the most common method is to use a parallel plate measuring system.

A characteristic feature of the cone-plate geometry is the possibility to achieve a constant shear rate in the entire fluid volume. This property is particularly valuable when testing non-Newtonian fluids. In the case of MF, this geometry is not preferred, because their rheological properties may depend on the dimensions of the measurement gap [**L. 9**]. This applies, in particular, to the magnetorheological fluids. This geometry was used in the past for rheological measurements in the case of ferrofluids [**L. 10**]. With this geometry, another problem is related to the space occupied in the measuring chamber. Pivots with flat-plates take less space and larger measuring chambers increase the electromagnet power. There are also rheometers for testing magnetic fluids based on the two cylinder system [**L. 11**]. In this case, the rheological properties for high shear rates (up to 10^6 s^{-1}) can be determined. It is similar in the case of rheometers based on the hard drive [**L. 12**] or brake [**L. 13**] construction for magnetorheological fluids.

Currently, the majority of studies on magnetic fluids are carried out for two-parallel plate geometry [**L. 14, 15**]. However, this system does not guarantee a constant value of the magnetic field [**L. 16**]. In order to obtain reliable measurements, an additional non-magnetic distance, separating the electromagnet core and magnetic fluid, is required [**L. 17**]. This element, however, reduces the shear rate range at which measurements can be made, because the magnetic fluid is ejected from the working gap as a result of the centrifugal force. Knowledge of the magnetic field distribution is very important when designing this type of measurement system and verifying the reliability of the obtained rheological parameters.

The paper presents the results of numerical simulations of the magnetic field distribution in the test chamber for testing the rheological properties of magnetic fluids. The influence of selected parameters was investigated. Attention was paid to such aspects as obtaining the most uniform distribution of the magnetic field, and maximizing the value of this parameter. The results of numerical analyses were compared with the results of gaussmeter measurements.

ANALYZED GEOMETRY

Simulations and measurements of the magnetic field were carried out on the test cell shown in **Fig. 1**. It is a part of the test rig used in studies of magnetic fluid rheological properties [**L. 18**].

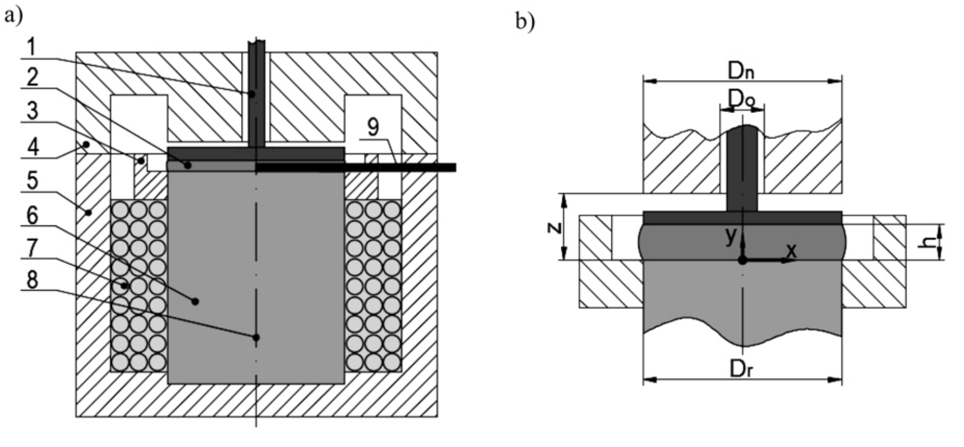

Fig. 1. a) the scheme of the measuring cell, b) geometric parameters of the parallel plate geometry
Rys. 1. a) schemat komory pomiarowej, b) parametry geometryczne układu płytka–płytka

The examined MF (Pos. 2) is placed between the core of the electromagnet (Pos. 6) and the rotating plate (Pos. 1). The value of the magnetic field was adjusted by changing the current supplying the electromagnet (Pos. 7). The magnetic circuit is closed by the upper (Pos. 4) and lower (Pos. 5) chamber housing. The rotating plate and fluid container (Pos. 3) are made of a material with non-magnetic properties. In this version, the diameter of the core (D_r) equals the diameter of the upper casing (D_n) $D_r = D_n = ø45$ mm. The hole diameter $D_O = ø10$ mm, and the height of the air gap (z) may vary within the range of 7–12 mm, depending on the thickness of the distance between the lower and upper chamber housing. In turn, the size of the gap (h) is determined, depending on the type of tests being carried out, because the plate is able to move and rotate according to the axis (Pos. 8).

NUMERICAL MODELLING

Numerical modelling is a convenient method to determine the magnetic field distribution in magnetic circuits. It is difficult to determine it on the basis of analytical calculations, due to the non-linear nature of the magnetic properties of magnetic circuit elements. It also enables the magnetic field parameters to be determined in places where the sensor has no access. The analyses were performed by using the finite element method, with ANSYS 14.5 software.

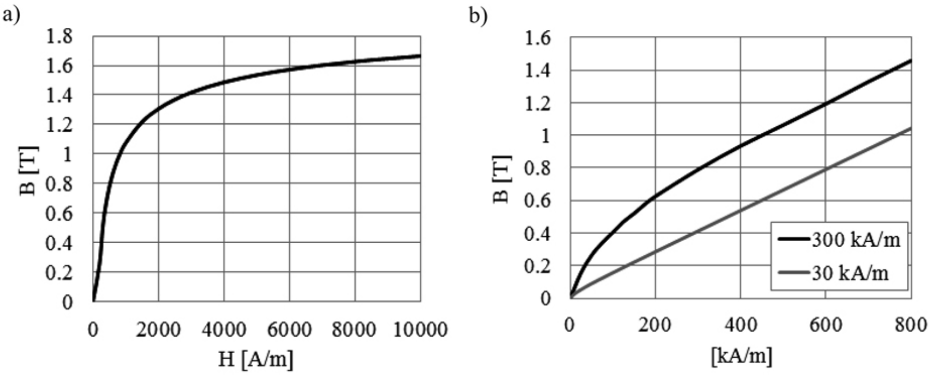

Fig. 2. B-H curves adopted for simulation tests: a) steel, b) magnetic fluids

Rys. 2. krzywe B–H przyjęte do badań symulacyjnych: a) stal konstrukcja, b) ciecze magnetyczne

The plate-plate system was modelled as an axially symmetric problem. The mesh size in the region of the measuring gap was an average size of 0.2 mm. The Dirichlet zero boundary conditions were introduced, i.e. the magnetic flux direction was assumed to be parallel to the edges of the analysed area, and the flux value at the boundaries of the area was assumed a value of zero.

In order to obtain the correct numerical solution, it was necessary to adopt appropriate magnetization characteristics. This applies to elements made of ferromagnetic material and a magnetic fluid. For steel elements, the B-H curve characteristic for structural steels with a carbon content of up to 0.27% was assumed (**Fig. 2a**). In turn, in order to assess how the presence of magnetic fluid affects the value of the magnetic field, B-H curves (**Fig. 2b**), characteristic for ferrofluids (magnetization saturation M_S = 30 kA/m) and magnetorheological fluids (M_S = 300 kA/m), were taken into account.

Simulation verifications were carried out by means of measurements on a real object, using a FH55 teslometer equipped with a 2 mm measuring probe. The probe (**Fig. 1**, Pos. 9) was inserted into the test chamber through a hole made in the housing. By means of a screw mechanism (not shown in the figure) equipped with a displacement transducer, the probe was moved along the radius of the electromagnet core.

Simulation and measurements with a sensor, in the case of current in the coil I = 3 A, two heights of z = 7 and 10 mm, without modelling the magnetic fluid, are shown in **Fig. 3**. The results obtained are very consistent.

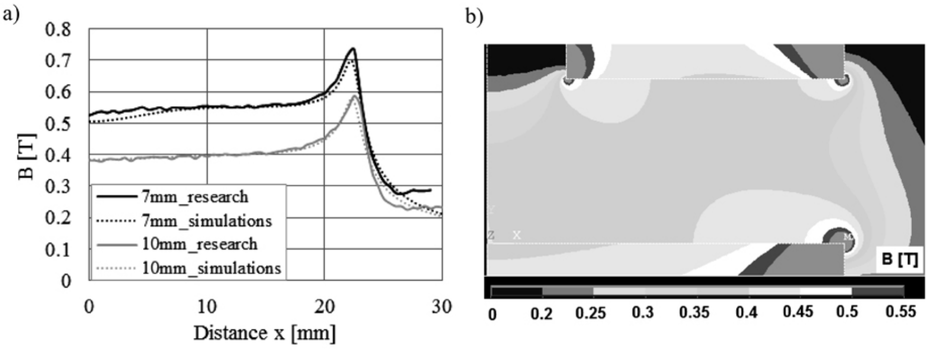

Fig. 3. a) magnetic induction results obtained by numerical simulation and measurements with a sensor for different heights (z), b) magnetic induction contour plot in case z = 10 mm, (gray color means a value above 0.55 T)

Rys. 3. a) porównanie wyników indukcji magnetycznej otrzymanej na drodze symulacji numerycznych oraz pomiarów czujnikiem dla różnych wysokości (z), b) konturowy wykres rozkładu indukcji magnetycznej w przypadku z = 10 mm, (kolor siwy oznacza wartość powyżej 0.55 T)

In the range of 0–15 mm, the magnetic induction value is approximately constant. However, for a length of 22.5 mm, there is a local increase in value in the edge region of the pole piece. The contour plot of the magnetic field distribution is shown in **Fig. 3b**.

RESULTS

The first part of the simulation was concerned with determining the influence of the distance from the face of the electromagnet on the magnetic induction peak observed in the region of the edge of the electromagnet core. The analyses were carried out for an air gap with a height of z = 10 mm and current of I = 3 A. The results of the simulation are shown in **Fig. 4a**. The distribution of magnetic induction at a distance of y = 0.02 mm is characterized by the presence of a large peak close to the edge of the core of the electromagnet. This is related to the presence of a sharp edge in this area. The magnetic induction peak value is approximately 4 times higher than the value of this parameter near the core axis. By analysing the distribution of magnetic induction at a distance of y = 1.5 mm, it can be seen that the peak value is significantly reduced, and at a distance of y = 3 mm, this peak disappears.

It should be noted that, as the distance "y" increases, in the region of the electromagnet axis (x = 0–4 mm), a decrease in the magnetic induction value is observed. This is due to the fact that, while moving away from the face area, the distance to the upper chamber housing decreases. In this region, there is a hole with a diameter D_O where the rotating plate is present.

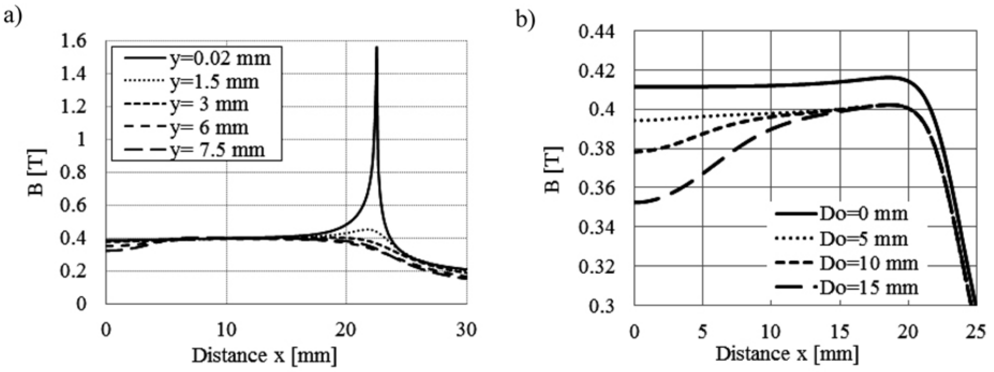

Fig. 4. Distribution of magnetic induction, I = 3 A, z = 10 mm: a) different heights y, b) different hole diameter D_O (determined for y = 3 mm)

Rys. 4. Rozkład indukcji magnetycznej, I = 3 A, z = 10 mm: a) dla różnych odległości „y", b) dla różnych średnic otworu D_O (wyznaczono dla y = 3 mm)

Figure 4b presents the results of the simulation analysis where the impact of the D_O diameter on the magnetic induction in the working gap is shown. In the absence of an opening, the most uniform distribution is obtained. The hole with a diameter of only D_O = 5 mm causes a decrease in the magnetic induction over the entire core diameter. In the case of the D_O = 15 mm hole, the value of the magnetic induction in the axis region is 12% lower in relation to its value near the edge of the analysed geometry.

Based on the results presented in **Fig. 4a**, it can be deduced that, in order to ensure an even distribution of magnetic induction in the region of the working gap, it is advantageous to place the test fluid at some distance from the face of the electromagnet core. It is possible to implement this type of solution by using a distance with appropriate thickness in the form of a plate with paramagnetic properties placed on the face of the electromagnet core.

Another method that influences the magnetic field distribution may be to form an appropriate shape of the core geometry. **Fig. 5** presents a contour plot of the magnetic induction distribution in the unmodified system (**Fig. 5a**) and after surface modification (**Fig. 5b**). The areas marked in **Fig. 5** (marked as A) are regions with increased magnetic induction (grey colour means a value above 0.41 T). The use of modification with a diameter of ø10 mm and a height of 0.5 mm means that, in the area for the height of y = 2.6–4.3 mm and the distance x ≈ 19 mm, the magnetic induction has a constant value – **Fig. 5b**. The modification resulted in a reduction in the case of magnetic induction change caused by the opening in the upper housing. Moreover, a limitation of the peak value at the edge of the electromagnet core was obtained.

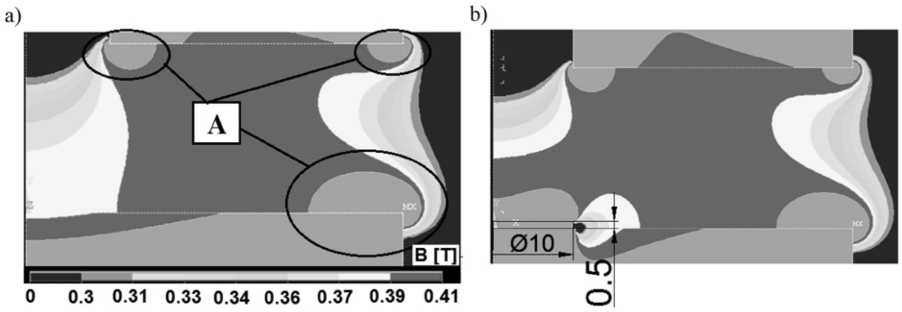

Fig. 5. Magnetic induction contour plot z = 7 mm, I = 3 A: a) without modification of the core surface, b) with modification of the core surface

Rys. 5. Konturowy rozkład indukcji magnetycznej z = 7 mm, I = 3 A: a) bez modyfikacji powierzchni rdzenia, b) z modyfikacją powierzchni rdzenia

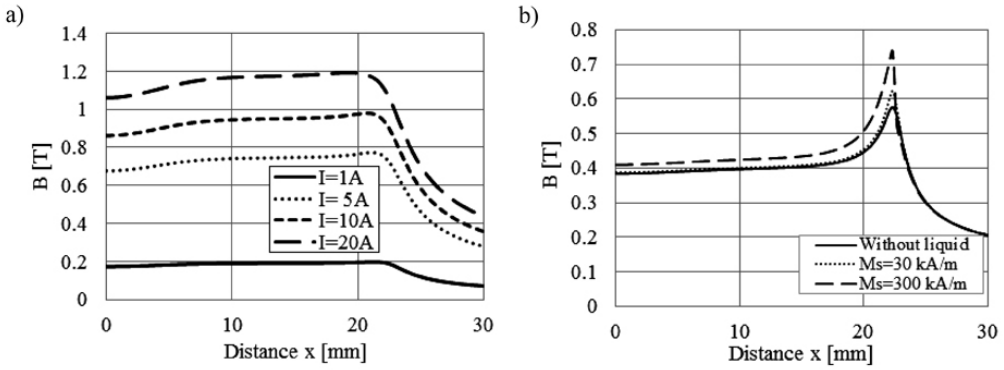

Fig. 6. Distribution of magnetic induction: a) z = 7mm, y = 1.5 mm, for different values of the current in the coil, b) z = 10 mm, y = 0.06 mm, I = 3A, for different magnetic fluids

Rys. 6. Rozkład indukcji magnetycznej: a) z = 7 mm, y = 1,5 mm, dla różnych wartości prądu w cewce, b) z = 10 mm, y = 0,06 mm, I = 3 A, dla różnych cieczy magnetycznych

In systems for testing magnetorheological fluids, high magnetic field values are sought. Currently produced MF can achieve magnetic saturation with a magnetic field induction even above 1.2 T. In the analysed system, it is possible to obtain such high induction values by reducing the height of the air gap "z" or by increasing the current in the electromagnet winding. However, due to the maintenance of adequate strength and stiffness of the rotating plate, there is a significant limitation on reducing the height of the "z" gap.

The influence of the current values I = 1, 5, 10, and 20 A is shown in **Fig. 6a**. The maximum value of 1.2 T (x = 20 mm) was obtained for I = 20 A. In the system under consideration, the electrical resistance of the coil was about 7 Ω. In order to achieve this value, it would be necessary to use a power source with a power of at least 2800 W.

It should also be noted that the value of magnetic induction in the fluid region (height h) also depends on the magnetic properties of the magnetic fluid being tested. **Fig. 6b** presents the results of simulations carried out for the case of magnetic fluid modelling in the working gap with different saturation magnetization values. In the case of magnetic fluid MS = 30 kA/m (typical for ferrofluids), the magnetic induction increase is about 9% and only in the case of the peak in the electromagnet core edge. In this region, for fluid with MS = 300 kA/m (a typical value for MR fluids), this increase is about 28%. There is also an increase in magnetic induction in the remaining region of the analysed geometry by about 30 mT.

CONCLUSIONS

The development of measuring system constructions used to determine the rheological properties of magnetic fluids is a complex issue. The use of MES simulation tools for this purpose is an important stage in the implementation of the design and construction process. In the present case, a good agreement was obtained between the results of numerical simulations and those of measurements carried out on the real object.

Systems of this type should ensure an even magnetic field distribution in the working gap. For this purpose, it is necessary to adopt the appropriate shape of the test chamber elements forming the magnetic circuit.

In order to obtain the highest magnetic induction values, it is beneficial to strive for the smallest air gap height (z) and to choose elements of the magnetic circuit from materials with a high saturation magnetization value. It is also possible to increase the magnetic induction by reducing the diameter of the hole in the upper housing. Such a solution faces a limitation due to the need to ensure sufficient strength and stiffness of the rotating plate.

In the system under consideration, there were regions of local increases in magnetic induction on the edges of magnetic circuit elements. This phenomenon can be limited in technical solutions by rounding at the edges. It should be noted, however, that, in some solutions, this effect may be desirable because it allows the self-sealing effect to be achieved, i.e. to limit the outflow of magnetic fluid from the bearing gap due to the presence of a magnetic barrier.

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